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Runoff Prediction Using an Aggregation Hydrology Model on Seulimum River Sub Watershed, Aceh Province, Indonesia

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Abstract – The objective of the present study was to predict the runoff in Seulimeum River sub watershed by utilizing an aggregation hydrology model. The method in this research consisted of field observation, data and map collection, model test, and data analysis. Some parameters were used as inputs on the model, such as; maximum and actual groundwater storage, soil moisture, and the constant of soil moisture k(t). The aggregation hydrology model was tested using 3 (three) statistical parameters, such as; determination coefficient (R^2), biased percentage (P_{BIAS}), and Nash-Sutcliffe coefficient (E_{NS}). The result shows that the minimum runoff occured in 1998 was 70.22 mm and the maximum runoff occurred in 1987 was 759.12 mm. The model tested showed that the aggregation hydrology model had a good performance in predicting the discharge of Krueng Seulimemum Sub Watershed; the R^2, P biased, and E_{NS} resulted 0.92, -5.21%, and 0.90, respectively.
Keywords: Runoff; Aaggregation hydrology model; Seulimeum River Sub Watershed

Introduction

In general, runoff prediction can be obtained by using direct and indirect measurement. The former uses flow metering device such as current meter while the latter uses mathematical equations from a simplest to a very complex model to predict runoff from certain area. A hydrology model is a very effective way to understand the hydrologic processes. Most of the model can be classified either into empirical, conceptual or physical model. An aggregation hydrology model was developed to study watersheds based on their soil characteristics. The model is mainly utilized to determine the amount of runoff produced by a watershed. Previous application in Goseng Subwatershed showed that the predicted runoff of the aggregation model was statistically acceptable compared to observed runoff (Setyawan, 2008).

According to Wagener *et al.* (2001) a hydrology model is an effective tool to study and to comprehend the hydrology processes. Some studies have been conducted in modeling, identifying and controlling the environmental systems, and in a catchment scale in particular (Young, 1978; Young, 2003) and the hydrological responds at vegetation changes in a catchment scale (Zhang *et al.*, 2001). Upward and downward approaches have been used in hydrological prediction (Sivapalan *et al.*, 2003; Zhang *et al.*, 2001).

The Seulimeum River sub watershed is a part of Aceh River watershed; it is situated at the upperstream of Krueng Aceh in Aceh Besar District, Aceh Province, Indonesia. Seulimeum River sub watershed is geographically located 95° 30 – 95° 45 E and 5° 15 – 5° 30 N. The area of Seulimeum River sub watershed is about 25.804,22 ha (258.04 km^2) or 13.2 % of Aceh River watershed area. It topographically consists of various slopes, from flat (0-8%), tilt (8-15%), slightly steep (15-25%), steep (25-45%), and highly steep (slope >45%. This upperstream plays an important rule as the water source for Aceh Besar District and Banda Aceh City and its surrounding areas. Presently no study on the runoff prediction was reported; hence the objective of present study was to predict the runoff in Krueng Seulimum Sub Watershed by utilizing an aggregation hydrology model.

Materials and Methods

The primary data was derived from observation in the field, by conducting soil sampling collection. Soil samples were analyzed in Laboratory of Soil Physics, Faculty of Agriculture, Syiah Kuala University, while the secondary data was derived from the relevant agencies, such as land use map, obtained from Watershed Management Agency (Balai Pengelolaan DAS Krueng Aceh) and climatology data was obtained from Meteorology Climatology and Geophysics Agency (Badan Metereologi Klimatologi dan Geofisika/ BMKG) of Blang Bintang, and monthly observed discharge data was collected from Water Resources Agency (BWSS I).

The aggregation of hydrology model used as inputs were potential evaporation, maximum groundwater storage, soil moisture, actual groundwater storage, runoff and soil moisture constant. Furthermore, the model performance was evaluated by using statistical analysis. Calculation method to find data as the input parameter to the hydrology model is as follows (Eqution. 1):

Potential Evapotranspiration (ETP) was calculated using Thornwaite equation as mentioned in formula (1) (Arsyad, 2006).

$$\mathrm{ETP} = 1.6\left(\frac{10t}{I}\right)^{a} \quad \text{.......(1)}$$

Where, t= daily temperature (°C), I= monthly heat index, a= 0.000000675 I^3 – 0,0000771 I^2 + 0,01792 I + 0,49239

where:

$$I = \left(\frac{t}{5}\right)^{1,514} \quad \text{.......(2)}$$

The maximum groundwater storage (PR max) was calculated using formula (3). The value of PR max depends on the runoff curve number (CN) (Setyawan, 2008).

$$\mathrm{PR\ max\ (S)} = \frac{25400}{\mathrm{CN}} - 254 \quad \text{.......(3)}$$

Where, PR max= maximum storage capacity (S), CN = Runoff Curve Number.

Soil moisture was predicted using formula (4). It depends on the values of precipitation and maximum storage capacity (Setyawan, 2008).

$$\mathrm{TR} = \frac{(\mathrm{P}-0{,}2\ \mathrm{PR\ max})^2}{(\mathrm{P}-0{,}2\ \mathrm{PR\ max}) + \mathrm{PR\ max}} \quad \text{.......(4)}$$

Where, TR= soil moisture, P= precipitation, PR max = maximum storage capacity

Actual Groundwater Storage (PR) was calculated using formula (5) by considering the value of P, PRmax and TR (Setyawan, 2008).

$$\mathrm{PR} = \mathrm{P} - 0{,}2\ \mathrm{PR\ max} - \mathrm{TR} \quad \text{.......(5)}$$

Q runoff (Setyawan, 2008)

$$Q_{runoff} = \frac{\mathrm{TR}}{k(t)} \quad \text{.......(6)}$$

Where, TR= soil moisture, k (t)= soil moisture constant

The value of k(t) was obtained from hourly precipitation data. However, if it was available, Haspers and Der Weduwen methods (Susilowati and Kusumastuti, 2010) could be used to calculate rainfall intensity. The formula is as follows:

$$R_i = X_t\left(\frac{1218t+54}{X_t(1-t)+1272t}\right) \quad \text{.......(7)}$$

Where, t= rainfall duration in hour, $X_{t=}$ the chosen maximum rainfall. For rainfall intensity:

$$I = \frac{R}{t} \quad \text{.......(8)}$$

For $1 \leq t < 24$ hour:

$$R = \sqrt{\frac{11300t}{t+3.12}} \left[\frac{R_i}{100}\right] \quad (9)$$

Where, I= rainfall intensity (mm/hour), R_i= rainfall according to Haspers and Der Weduwen (Susilowati and Kusumastuti, 2010), t= rainfall duration (hour), X_t= the chosen maximum daily rainfall (mm/day).

In this study, model perfomances were evaluated using coefficient of determination (R^2), biased percentage (P_{BIAS}), and coefficient of Nash-Sutcliffe (E_{NS}). Those parameters were then calculated using the following equations:

$$R^2 = \left[\frac{\sum_{i=1}^{n}(O_i-\bar{O})(P_i-\bar{P})}{\sqrt{\sum_{i=1}^{n}(O_i-\bar{O})^2}\sqrt{\sum_{i=1}^{n}(P_i-\bar{P})^2}}\right]^2 \quad (10)$$

$$P_{BIAS} = \frac{\sum_{i=1}^{n}(O_i-P_i)}{\sum_{i=1}^{n}O_i} \times 100 \quad (11)$$

$$E_{NS} = 1 - \frac{\sum_{i=1}^{n}(O_i-P_i)^2}{\sum_{i=1}^{n}(O_i-\bar{O})^2} \quad (12)$$

Where, R^2= coefficient of determination, P_{BIAS}= biased percentage, E_{NS}= coefficient of Nash-Sutcliffe (Nash and Sutcliffe, 1970), O= observation value, P= value obtained from model

Results and Discussions

In model of aggregation hydrology, the soil characteristic of a watershed determined the runoff values. The very influential soil characteristic is soil texture. Soil texture and land cover determines the Hydrologic Soil Group of a watershed. The soil sampling and Hydrologic Soil Group (HSG) of Seulimeum River sub watershed was shown in Figure 1 The CN values are the combination of land use and Hidrology Soil Group (HSG). Those values were obtained from the overlayed maps between map of land use (Figure 2) and map of Hydrology Soil Group (Figure 1). The CN of Seulimeum River was shown in Table 3.

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Table 1. Land cover on Seulimum River sub watershed

Land Cover	Area (km²)	Area (Ha)	Percentage (%)
Secondary dryland forest	65.70	6,570.35	25.46
Residential	0.04	3.95	0.02
Dryland agriculture	65.07	6,507.03	25.22
Savana	53.45	5,345.32	20.71
Rice field	11.97	1,197.44	4.64
Bush	59.48	5,948.49	23.05
Water body	0.07	6.85	0,03
Land clearing	0.76	75.55	0.29
Plantation	1.21	121.01	0.47
Mixed dryland agriculture	0.28	28.22	0.11
Total	258.04	25,804.22	100.00

Table 2. Soil characteristic of Seulimeum River sub watershed

Point	North Latitude	East Longitude	Percentage of Fraction			Texture	HSG
			Sand	Silt	Clay		
1	05°02'05"	095°36'34"	13	69	18	Silty Clay	D
2	05°23'04"	095°38'12"	43	27	30	Clayey loam	D
3	05°21'29"	095°39'28"	31	27	42	Clay	D
4	05°22'33"	095°41'29"	19	21	60	Clay	D
5	05°18'34"	095°42'38"	12	61	27	Silty Clay	D
6	05°22'20"	095°33'49"	71	19	10	Sandy Loam	A
7	05°21'30"	095°34'53"	87	9	4	Loamy Sand	B
8	05°22'42"	095°36'33"	76	20	4	Loamy Sand	B
9	05°21'52"	095°36'40"	17	52	31	Silty Loam Clay	D
10	05°22'05"	095°38'25"	14	52	34	Silty Loam Clay	D
11	05°21'40"	095°40'18"	19	64	17	Silty Loam	C
12	05°21'22"	095°40'50"	64	24	12	Sandy Loam	A
13	05°20'36"	095°41'47"	34	22	44	Clay	D
14	05°23'35"	095°41'48"	26	32	42	Clay	D
15	05°24'09"	095°41'51"	42	28	30	Clayey Loam	D

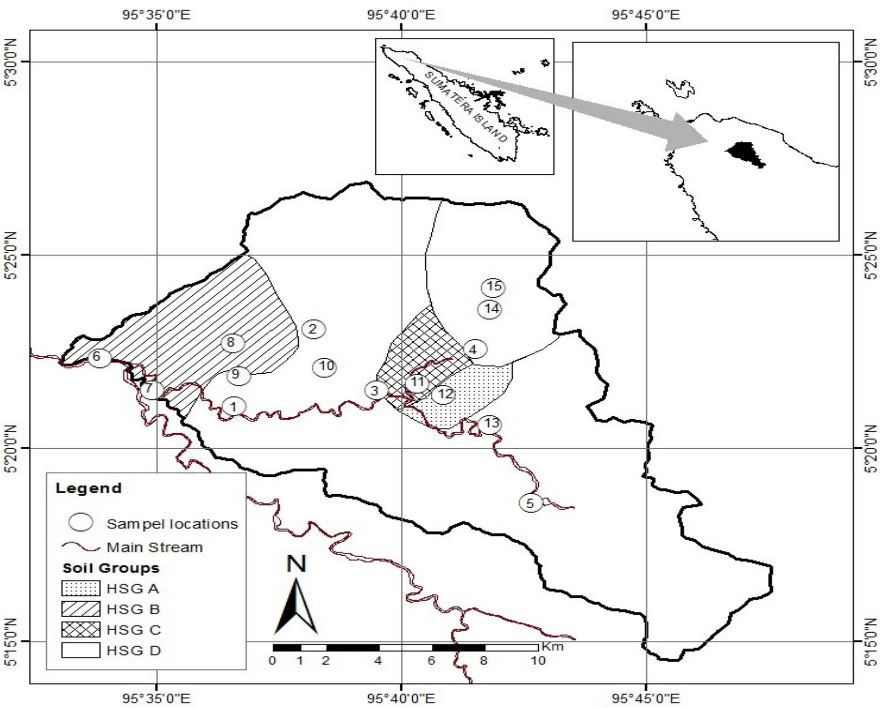

Figure 1. Soil sampling points and hydrologic soil group (HSG) of Seulimemum River sub watershed

Table 3. CN of Seulimeum River sub watershed

HSG	Land Use	CN	Area (km^2)	Percentage (%)
A	Residential	51	0.0005	0.0002
A	Dryland agriculture	62	3.74	1.45
A	Savana	30	2.06	0.80
A	Rice field	100	0.0002	0.0001
A	Bush	68	1.26	0.49
B	Bush	79	0.35	0.14
B	Residential	68	0.04	0.02
B	Savana	58	4.35	1.69
B	Water body	100	0.07	0.03
B	Dryland agriculture	71	16.03	6.21
B	Rice field	100	11.28	4.37
C	Bush	86	1.48	0.57
C	Bush	74	0.02	0.01
C	Savana	71	0.66	0.25
C	Dryland agriculture	78	0.66	0.25
D	Secondary dryland forest	83	65.66	25.44
D	Plantations	77	1.21	0.47
D	Dryland agriculture	81	44.64	17.30
D	Mixed dryland agriculture	91	0.28	0.11
D	Savana	78	46.39	17.98
D	Rice field	100	0.69	0.27
D	Bush	89	56.39	21.85
D	Land clearing	80	0.73	0.28
	Average CN	81.63	258.04	100.00

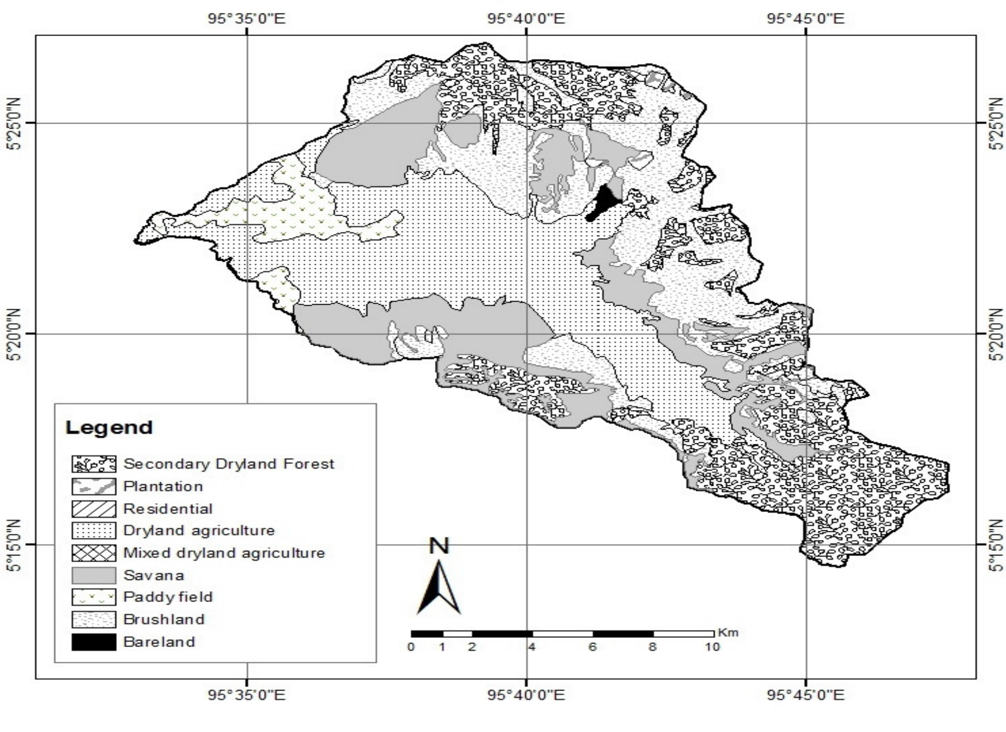

Figure 2. Land use of Seulimeum River sub watershed

The average of CN was obtained by multiplying the CN value of each land use and Hydrological Soil Group with the area, then divided by the total of watershed area. This method mathematically is written in the following equation:

$$\overline{CN} = \frac{\sum_{j=1}^{n}(CN_j A_j)}{\sum_{j=1}^{n} A_j} \quad \text{.......... (13)}$$

Where, CN = Curve Number, A= Area of Sub Watershed (km^2). The value of the actual storage that occured in Aceh River sub watershed was shown in Table 4.

Table 5 shows the value of k (t) values are not significantly different because the precipitation data was derived from the daily prepitation. In spite of daily precipitation, the hourly precipitation data should be used. Therefore, the value of k(t) should have the same tendency. The value of k(t) was used to calculate the runoff occurred in Krueng Seulimum Sub Watershed. The greater value of k(t) indicates smaller runoff and vice versa. The changes of soil moisture is due to saturated flow on the surface that added into the soil. In other words, the changes of soil moisture is the discharge prediction without any influences from soil moisture constant (k(t)). The changes of soil moisture is influenced by precipitation and maximum storage. If the changes of soil moisture was greater, the runoff would occur greater as well. The value of the changes of soil moisture (TR) was shown in Table 7.

Table 4. Daily actual storage on Seulimum River sub watershed

Year	PR (mm)	Year	PR (mm)
1987	0.90	1994	0.79
1988	0.42	1995	0.60
1989	0.22	1996	0.90
1990	0.37	1997	0.72
1991	0.42	1998	0.34
1992	0.31	1999	0.34
1993	0.41	2000	0.62

Table 5. Soil moisture constant k(t) on Seulimum River sub watershed

Year	k(t)	Year	k(t)
1987	0.568	1994	0.569
1988	0.569	1995	0.568
1989	0.569	1996	0.568
1990	0.569	1997	0.568
1991	0.568	1998	0.569
1992	0.569	1999	0.568
1993	0.570	2000	0.567

Table 6. The changes of soil moisture

Year	TR (mm)	Year	TR (mm)
1987	1,499.32	1994	385.62
1988	1,495.45	1995	334.17
1989	1,351.42	1996	329.11
1990	1,373.01	1997	244.70
1991	1,334.17	1998	138.81
1992	1,196.78	1999	152.57
1993	1,296.78	2000	417.08

From Table 6., it can be found that the highest TR is 1,499.32 mm obtained in 1987, whereas the lowest TR is 138.81 mm obtained in 1998. The TR value decreased during 1993 to 1994 years. The value of runoff increased to the value of base flow which approached the actual debit. The changed value is the value of base flow and the value of decreasing daily base flow. The value of base flow would increase if precipitation exceed the maximum storage.

The value of recharge prediction was obtained from the aggregation hydrology model and was compared to the actual groundwater recharge that recorded in an automated recharge recorder. The parameter of E_{NS} (Nash-Sutcliffe coefficient) show how good the model in order to explain the variations in observation data compared to the value of resulted model. If the value of E_{NS} is negative or nearly zero, the model has poor performance or could not be counted on. The performance of aggregation hydrologycal model for Seulimum River sub watershed shows the model is in good categorization, presented in Table 7. The discharge comparison between observed and predicted discharges is presented in Figure 3.

Table 7. Weigthed CN scenario on Seulimum River sub watershed

Year	Weighted CN	PR Max (mm)	Base Flow (mm)	Constant of decreasing base flow (mm)	R^2	P_{BIAS}	E_{NS}
1987-1993	86.39	40	6	0.001	0.92	-5.21%	0.90
1993-2000	77.20	75	1	0.001			

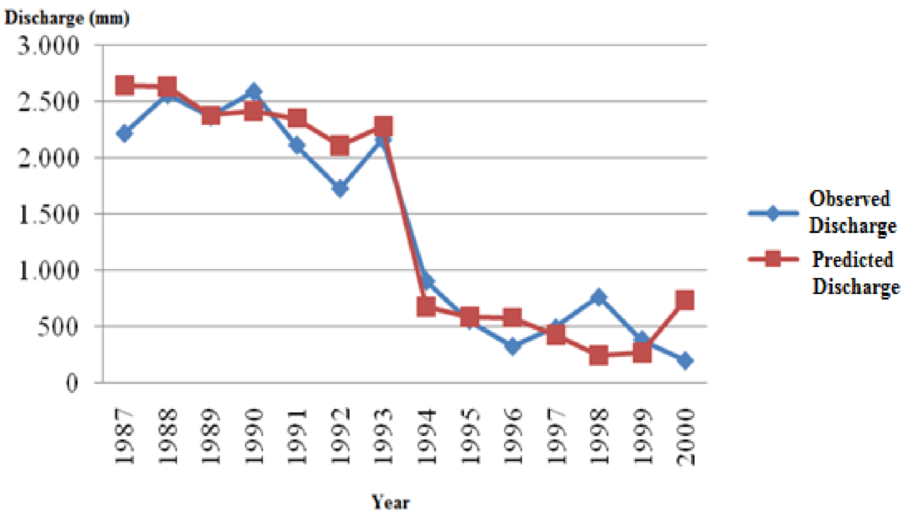

Figure 3. A Discharge comparison according observation years

The aggregation hydrology model

Lane (1993) suggests that the aggregation hydrology model is a reliable parameter estimation which promising an improved time series model started with smaller time increment that infers the appropriate models and parameters for the aggregated time series. But, in contrary, Hsu *et al.* (1998) mentions that since the statistics of the hydrological model is determined by the watershed average of the hydrological parameters, it is difficult to conclude whether the modeling results are due to errors in the input of hydrological parameters obtained from soil database or due to errors resulting from the aggregation processes in the model. In addition, Heuvelink and Pebesma (1999) mentioned that many models used in soil science suffer not only from error input but also from model error, which is support and case dependent. Case dependency means that the model error can only realistically be assessed through validation. In the validation there also occurs a major problem which is the validation data often collected at a much smaller support than the agrregated model prediction.

Runoff prediction on Seulimum River sub watershed

Figure 4 shows that the lowest runoff occurred in 1987, whereas the highest runoff occurred in 1998. The rainfall values in 1987 and 1998 are not the highest nor the lowest values, the runoff values are different from the rainfall values. This is due to the usage of climatology data derived from Indrapuri Station instead of from Blang Bintang Climatology Station. This also indicates that the probability of rainfall were not recorded properly at the appointed climatological stations. The lack of data such as observed discharges and rainfall, soil and land use types as well as rainfall intensity is the primary problem and challenge in analysing rainfall-runoff model in Province of Aceh (Basri, 2013).

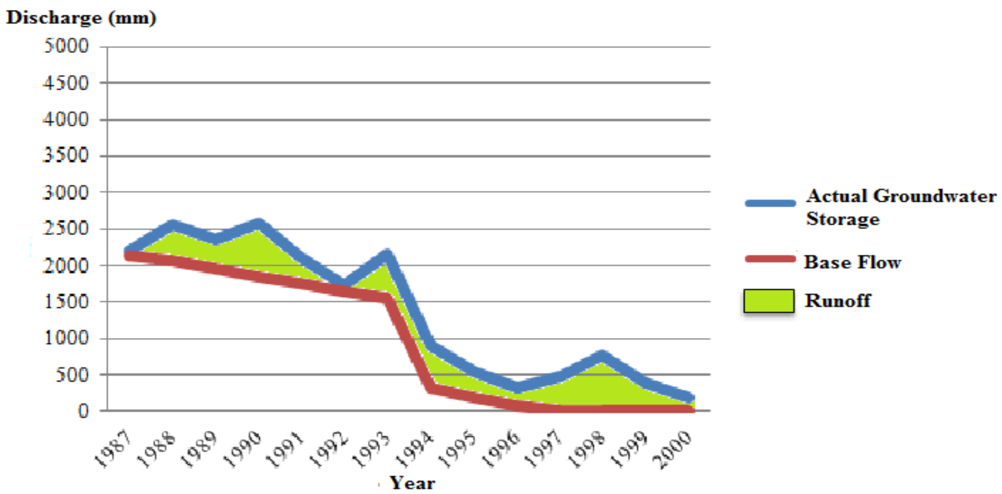

Figure 4. Runoff prediction on Seulimum River sub watershed

Conclusion

The model of aggregation hydrology can be used to predict runoff from areas where data is limited. This model has a good performance to predict the discharge of Krueng Seulimum subwatershed, where R^2, P biased, and ENS were 0.92, -5.21% and 0.90, respectively.

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